QI 15: Quantum Computing Theory

Time: Wednesday 9:30–13:00 Location: HFT-FT 101

Invited Talk QI 15.1 Wed 9:30 HFT-FT 101

Computationally Universal Phases of Quantum Matter — •Robert Raussendorf[1], Cihan Okay[2], Dongsheng Wang[3], David Stephen[4], and Hendrik P Nautrup[5] — [1]Leibniz Universität Hannover — [2]Bilkent University Ankara, Turkey — [3]Chinese Academy of Sciences, China — [4]University of Colorado, Boulder, USA — [5]University of Innsbruck

In measurement based quantum computation, the computational power hinges on the resource quantum state. Some states give universal computational power, but most states provide no computational power at all [1]. This picture changes in the presence of symmetry. Namely, for phases of ground states of symmetric Hamiltonians, i.e., symmetry-protected topological (SPT) phases, it has been found that computational power is uniform across those phases. This observation gave rise to the term 'computational phases of quantum matter* [2,3]. In my talk, I give a short history of this line of research, and then present examples of symmetry protected quantum phases that have universal computational power [4 - 6].

[1] D. Gross, S. T. Flammia, and J. Eisert, PRL 102, 190501 (2009).
[2] A. C. Doherty and S. D. Bartlett, PRL 103, 020506 (2009).
[3] A. Miyake, Phys. Rev. Lett. 105, 040501 (2010).
[4] R. Raussendorf et al., Phys. Rev. Lett. 122, 090501 (2019).
[5] D.T. Stephen et al., Quantum 3, 142 (2019).
[6] A.K. Daniel, R.N. Alexander, A. Miyake, Quantum 4, 228 (2020).

QI 15.2 Wed 10:00 HFT-FT 101

Mapping quantum circuits to shallow-depth measurement patterns based on graph states — •Thierry Nicolas Kaldenbach[1] and Matthias Heller[2] — [1]German Aerospace Center (DLR), Institute of Materials Research, Cologne, Germany — [2]Fraunhofer Institute for Computer Graphics Research IGD, Darmstadt, Germany

The paradigm of measurement-based quantum computing (MBQC) starts from a highly entangled resource state on which unitary operations are executed through adaptive measurements and corrections ensuring determinism. This is set in contrast to the more common quantum circuit model, in which unitary operations are directly implemented through quantum gates prior to final measurements. In this work, we incorporate concepts from MBQC into the circuit model to create a hybrid simulation technique, permitting us to split any quantum circuit into a classically efficiently simulatable Clifford-part and a second part consisting of a stabilizer state and local (adaptive) measurement instructions, a so-called standard form, which is executed on a quantum computer. We further process the stabilizer state with the graph state formalism, thus enabling a significant decrease in circuit depth for certain applications. We show that groups of fully commuting operators can be implemented using fully-parallel, i.e., non-adaptive, measurements within our protocol. Finally, we demonstrate the utility of our technique on two examples of high practical relevance: the Quantum Approximate Optimization Algorithm (QAOA) and the Variational Quantum Eigensolver (VQE).

QI 15.3 Wed 10:15 HFT-FT 101

Quantum state preparation via engineered ancilla resetting — •Daniel Alcalde Puente[1,2], Felix Motzoi[1], Tommaso Calarco[1,2,3], Giovanna Morigi[4], and Matteo Rizzi[1,2] — [1]Forschungszentrum Julich - Institute of Quantum Control, Peter Grünberg Institut (PGI-8), Jülich, Germany — [2]Institute for Theoretical Physics-University of Cologne, Köln, Germany — [3]Dipartimento di Fisica e Astronomia - Universita di Bologna, Bologna, Italy — [4]Theoretical Physics- Department of Physics- Saarland University, Saarbrucken, Germany

In this study, we investigate a quantum resetting protocol for preparing ground states of frustration-free Hamiltonians. The protocol uses a steering Hamiltonian for local coupling to ancillary degrees of freedom, which are periodically reset. For short reset times, the dynamics resemble a Lindbladian with the target state as its steady state. We use Matrix Product State simulations and quantum trajectory methods to assess the protocol's efficiency in preparing the spin-1 Affleck-Kennedy-Lieb-Tasaki state, focusing on convergence time, fidelity, and energy evolution at various reset intervals. Our findings indicate that entanglement with the ancillary system is crucial for rapid convergence, with an optimal reset time for peak performance. The protocol also demonstrates robustness against small deviations in reset time and dephasing noise. Our results suggest that quantum resetting could be more advantageous than other methods like quantum reservoir engineering in certain contexts.

QI 15.4 Wed 10:30 HFT-FT 101

Shot noise reduction by problem-tailored measurements — •Timo Eckstein[1,2], Refik Mansuroglu[1], Martin Kliesch[3], and Michael J. Hartmann[1,2] — [1]FAU Erlangen-Nürnberg, Germany — [2]MPI for the Science of Light, Germany — [3]TU Hamburg, Germany

The preparation and measurements of low-energy eigenstates of strongly correlated many-body systems are considered an auspicious real-world use case of near-term quantum computers. Such quantum states feature nontrivial long-range entanglement, which cannot be efficiently described using classical methods but may still be prepared on quantum devices.

Here, we address the challenge of efficiently extracting information from the quantum device in such applications. Naive measurement schemes, like estimating eigenvalues of Pauli strings can require excessive amounts of measurements. These requirements are significantly reduced by our strategy.

In contrast to observable agnostic methods like shadow tomography, we focus on observable specific ones. Specifically, starting from tractable subsystems, we constructed measurements that are tailored for energy estimation of interacting quantum systems with local Hamiltonians. This construction leads to estimators with smaller variances compared to local Pauli bases. Indeed, in our numerical studies, we find linear variance improvements which translate to quadratic savings in the required number of measurements. We show this to hold analytically if constrained to positively correlated splitting or alternatively to Pauli-bipartitions.

QI 15.5 Wed 10:45 HFT-FT 101

Polynomial pre-processing for quantum singular value transformations — •Shawn Skelton and Tobias Osbourne — Leibniz Universität Hannover

Quantum signal processing (QSP), and its extension quantum singular value transformation (QSVT), are increasingly popular frameworks for developing fault-tolerant quantum algorithms. Despite their recent prominence in the literature, QSP implementations still struggle to complete a costly classical pre-processing step. Namely, one must select a set of $SU(2)$ rotation matrices for a given polynomial $P(x)$ using algorithms which rely upon either optimization or polynomial root-finding subroutines. These techniques either introduce undesirable constraints on the input polynomials or struggle with high-degree polynomials. Furthermore, this pre-processing can depend on how users design their problem, and notably on whether one works in the variable domain $z \in U(1)$ or $x \in [-1, 1]$. We introduce a new method for computing rotation matrices for the complex-variable case and compare the run-time and reliability of our technique to existing methods. Our benchmark functions are selected for their ubiquity in the literature - functional approximations used to implement matrix inversion, Hamiltonian simulation, and unstructured search with QSP. Because QSP/QSVT techniques are relatively new to the literature, we also consider the *ease of application* of each method and suggest best practices for new users.

15 min. break

QI 15.6 Wed 11:15 HFT-FT 101

Squeezing and quantum approximate optimization — •Gopal Chandra Santra[1,2], Fred Jendrzejewski[1,3], Philipp Hauke[2,4], and Daniel J. Egger[5] — [1]Universität Heidelberg, Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany — [2]Pitaevskii BEC Center and Department of Physics, University of Trento, Via Sommarive 14, I-38123 Trento, Italy — [3]Alqor UG (haftungsbeschränkt), Marquardstrasse 46, 60489 Frankfurt am Main, Germany — [4]INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, Trento, Italy — [5]IBM Quantum, IBM Research Europe - Zurich, Säumerstrasse 4, CH-8803 Rüschlikon, Switzerland

Although variational quantum algorithms provide fascinating

prospects in combinatorial optimization, the achievable performance and the role of quantum correlations therein remain unclear. We shed light on this open issue by establishing a tight connection between the quantum approximate optimization algorithm (QAOA) and the seemingly unrelated field of quantum metrology via generating squeezed states both numerically and on an IBM quantum chip while QAOA is tasked to solve MaxCut problems with increased precision. Such QAOA-tailored squeezing relates to quantum correlation in the form of entanglement; it permits us to propose a figure of merit for future hardware benchmarks, and it can resource-effectively boost the averaged final energy of QAOA optimization obtained in MaxCut of random graph instances. Further exploiting this connection between metrology and optimization may uncover solutions to prevailing problems and push the scope of precision in both fields.

QI 15.7 Wed 11:30 HFT-FT 101

Overlap Gap Property limits limit swaping in QAOA — •Mark Goh — Institute of Material Physics in Space, German Aerospace Center, Cologne, Germany — Institute for Theoretical Physics, University of Cologne, Cologne, Germany

The Quantum Approximate Optimization Algorithm (QAOA) is a quantum algorithm designed for finding approximate solutions to combinatorial optimization problem. Recent works on evaluating the performance of QAOA for q-spin glass models have been found to to beat semi-definite programming at layer $p = 11$ for the Sherrington–Kirkpatrick model (2-spin glass). In addition, the algorithm to evaluate the expectation value has time complexity $\mathcal{O}(p^2 4^p)$, independent of the input size in the large n limit.

We show that under the likely conjecture that Max-q-XORSAT on large-girth regular hypergraph exhibit the Overlap Gap Property (OGP), the swapping of limits in QAOA leads to suboptimal results. Numerical simulations of Max-q-XORSAT on large-girth regular hypergraph supports the conjecture as OGP is observed when the degree of a vertex is greater than q.

Furthermore, since the performance of QAOA for the pure q-spin model matches asymptotically for Max-q-XORSAT on large-girth regular hypergraph, we show that the average-case value obtained by QAOA for the pure q-spin model for even $q \geq 4$ is bounded away from optimality even when the algorithm runs indefinitely if the conjecture is true. This suggests that a necessary condition for the validity of limit swapping in QAOA is the absence of OGP.

QI 15.8 Wed 11:45 HFT-FT 101

Symmetry obstructions to the quantum approximate optimization algorithm — Sujay Kazi[1,2,3], Martin Larocca[2,4], Marco Farinati[5], Patrick J. Coles[6], Marco Cerezo[7], and •Robert Zeier[8] — [1]Courant Institute of Mathematical Sciences, New York University, New York, New York 10012, USA — [2]Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA — [3]Department of Electrical and Computer Engineering, Duke University, Durham, NC 27708, USA — [4]Center for Nonlinear Studies, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA — [5]Departamento de Matemática, FCEN, UBA - IMAS CONICET — [6]Normal Computing Corporation, New York, New York, USA — [7]Information Sciences, Los Alamos National Laboratory, Los Alamos, NM 87545, USA — [8]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), 54245 Jülich, Germany

The quantum approximate optimization algorithm (QAOA) approximates ground states related to the maximum-cut graph problem. We study symmetries and algebraic properties of QAOA ansätze. For the free (or multi-angle) ansatz, the Lie algebras observed for any connected graph split into six classes corresponding to path, cycle, bipartite, and remaining graphs. We predict that polynomially and exponentially deep quantum circuits will suffer from barren plateaus when the free ansatz is applied to the remaining graphs. But shallow circuits of logarithmic depth will likely lack the resources to approximately reach the ground state. Even for the so-called standard ansatz, we indicate why the effectiveness of QAOA might be negatively affected.

QI 15.9 Wed 12:00 HFT-FT 101

Discrete adiabatic quantum optimization — •Vanessa Dehn and Thomas Wellens — Fraunhofer Institut für Angewandte Festkörperphysik IAF, Freiburg, Deutschland

The Quantum Approximate Optimization Algorithm (QAOA) is a well-known candidate for solving combinatorial optimization problems more efficiently than classical computers in the current noisy intermediate-scale quantum (NISQ) era. The form of the QAOA circuit is inspired by adiabatic quantum computing (AQC) in terms of starting in the ground state of the mixing Hamiltonian, which is then gradually transferred to the ground state of the cost Hamiltonian by approximating the adiabatic annealing path via Trotterization for an increasing and very large iteration depth p. Therefore, the performance of QAOA is expected to improve with increasing p. However, recent studies [1] showed, that QAOA can exhibit a poor performance for large circuit parameters, even in the adiabatic limit.

To explain this behavior, a modification of the continous adiabatic theorem, namely the discrete adiabatic theorem, is applied, where the state evolves by applying a product of gradually varying unitaries. To understand the decrease of the ground state population, we track the population and population changes of each state throughout the whole protocol for different sets of parameters. Furthermore, we explore how these insights may be used in order to find optimized schedules for the QAOA angles.

[1] V. Kremenetski et al., arXiv:2305.04455 (2023).

QI 15.10 Wed 12:15 HFT-FT 101

Quantum optimization with quantum circuits — •Francesco Preti and Felix Motzoi — Forschungszentrum Jülich, Wilhelm-Jonen Strasse, Jülich

We study the possibility of sampling different types of gradients for NISQ optimization from quantum circuits. We show that in certain contexts, e.g. for certain numbers of parameters, we can obtain a faster sampling of gradient guesses that, although they lack the precision of standard gradients, still lead to fast, reliable optimization. We then apply our method to different types of cost functions to evaluate the quality of the optimization.

QI 15.11 Wed 12:30 HFT-FT 101

Efficient Amplitude Encoding of Classical Data — •Vittorio Pagni — Deutsches Zentrum für Luft - und Raumfahrt (Dlr), Deutschland

Although the theoretical advantages associated to quantum computers have been proved, whenever we want to apply the most efficient quantum algorithms to classical data or initialize our quantum circuit in a specific state, an efficient state preparation algorithm can prevent us from wasting the quantum speed up because of a computational bottleneck effect, especially for large classical vectors.
We present an improved version of a pre-existing (PhysRevResearch.4.013091) quantum amplitude encoding procedure that encodes the real or complex entries of a properly normalized classical vector $\vec{v} = (v_1, .., v_N)$ of length N into the amplitudes of a quantum state. Our approach generalizes the protocol to complex entries and it shows a quadratic time speed up with respect to the original. Furthermore, the procedure also allows for some flexibility in the way the intermediate operations are performed, so that it is possible to customize the balance between memory and time cost for the specific application. Depending on the data density $\rho(\vec{v}) = \sum_{i=0}^{N-1} \| \frac{v_i}{v_{max}} \|^2$, $\frac{1}{N} \leq \rho \leq 1$ of the classical input vector of length N and on the parallelization parameter M, $1 \leq M \leq N$, the number of qubits scales as $O(M \log_2 N)$ while the time cost increases as $O(\frac{1}{\sqrt{\rho}} \frac{N}{M} \log_2 \log_2 N)$, which has an upper bound of $O(\sqrt{N} \log_2 \log_2 N)$ in the worst case scenario.

QI 15.12 Wed 12:45 HFT-FT 101

Holonomic quantum computation: a scalable adiabatic architecture — Jose Carrasco, Tommaso Guaita, and •Clara Wassner — Dahlem Center for Complex Quantum Systems, Freie Universitat Berlin, 14195 Berlin, Germany

Holonomic quantum computation is a framework that exploits the geometric evolution within specific eigenspaces of a degenerate Hamiltonian to enact the unitary evolution of computational states. In this study, we present a scalable architecture consisting of a universal set of fully holonomic gates, specifically designed for quantum computations on contemporary experimental platforms. Notably, our proposal offers a straightforward implementation in Rydberg array experiments, capitalizing on the capability to manipulate atoms using tweezers. This renders the experimental realization of large-scale holonomic implementations feasible for the first time. Owing to their geometric nature, our gates exhibit promising resistance against certain faults. We conduct a comprehensive analysis of the geometric properties of these gates, giving systematic insight on the mechanisms of their noise robustness. To demonstrate the resistance of our gates, we conduct a range of simulations under various coherent and incoherent error models.